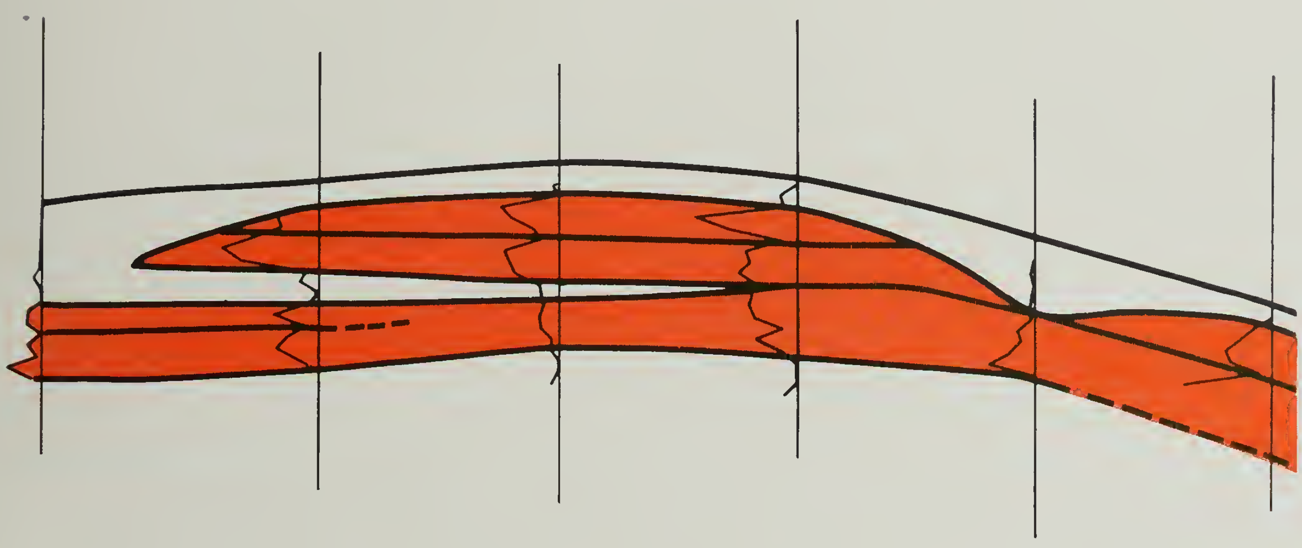
Improved Oil Recovery from the Aux Vases (Mississippian) Formation at Boyd Field, Jefferson County, Illinois

Hannes E. Leetaru



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ABSTRACT

Oil production at Boyd Field in Jefferson County, Illinois, is structurally and stratigraphically controlled. Principal production is from sandstones at depths of 2,050 feet in the Mississippian Yankeetown (Benoist) Formation and 2,150 feet in the Aux Vases Formation. Of the 130 wells in Boyd Field, 48 have produced from the Aux Vases reservoir. The original oil in place in the Aux Vases reservoir is estimated to have been 4.5 million barrels.

The field has 20 feet of anticlinal closure and is 2 1/2 miles long and 1 mile wide. The Aux Vases Formation at Boyd Field is approximately 40 feet thick. The reservoir sand occurs in the uppermost 20 feet of the formation and is typically limited in areal extent. Within one 10 acre well spacing (a distance of 660 feet) the sandstone facies may change into impermeable siltstones and shales. The Aux Vases Formation at Boyd Field was deposited in a tidally influenced, nearshore marine environment. The large degree of lateral and vertical compartmentalization of the reservoir is due to the lenticular nature of the sand bodies. Because of this reservoir compartmentalization, the Aux Vases Formation has recoverable mobile reserves that have not been affected by the current waterflood project.

Most of the wells that produce from the Aux Vases also were completed to produce from the Benoist reservoir. The Benoist reservoir has an active water drive and shows less pressure decline than the Aux Vases reservoir, which is a gas-solution drive. After the first 4 to 5 years of production, higher pressure within the Benoist reservoir impeded and at times completely curtailed Aux Vases production.

Pores in the Aux Vases reservoir are lined by a mixture of three types of clay minerals: mixed-layered illite/smectite, illite, and iron-rich chlorite. The mixed-layered illite/smectite can swell in freshwater, clog pore throats, and reduce permeability by more than 50%.

An understanding of the original reservoir management practices, in conjunction with detailed reservoir characterization, may allow operators to recover a greater percentage of the remaining mobile reserves. Boyd Field can serve as an example for oil fields that are laterally and vertically compartmentalized and have a multi-pay reservoir dually completed and with different reservoir pressures.

INTRODUCTION

Integration of the local reservoir geology with development history and production engineering allows development of a strategy for improving oil recovery in Boyd Field. Boyd Field is located in the northwest corner of Jefferson County at the western limit of oil production from the Mississippian Aux Vases Formation (fig. 1). The 1,200 acre field produces mostly from the Yankeetown (Benoist) and Aux Vases Formations (fig. 2) at depths of about 2,050 feet and 2,150 feet, respectively. (Sandstones of the Yankeetown Formation in the Illinois Basin are referred to as the Benoist sandstones by the oil industry; therefore, Benoist sandstone is the name used in this report.)

This study evaluates reservoir heterogeneity and the prospects of improved oil recovery in a field where previous reservoir management techniques have complicated the analysis. Most wells at Boyd Field were completed in both the Aux Vases and Benoist reservoirs. Consequently, no accurate way exists for separately estimating annual production from each zone. Minor production is also extracted from the Mississippian Renault Formation, the Mississippian Ste. Genevieve Formation, and the Ordovician Galena Group (Trenton). Boyd Field has produced more than

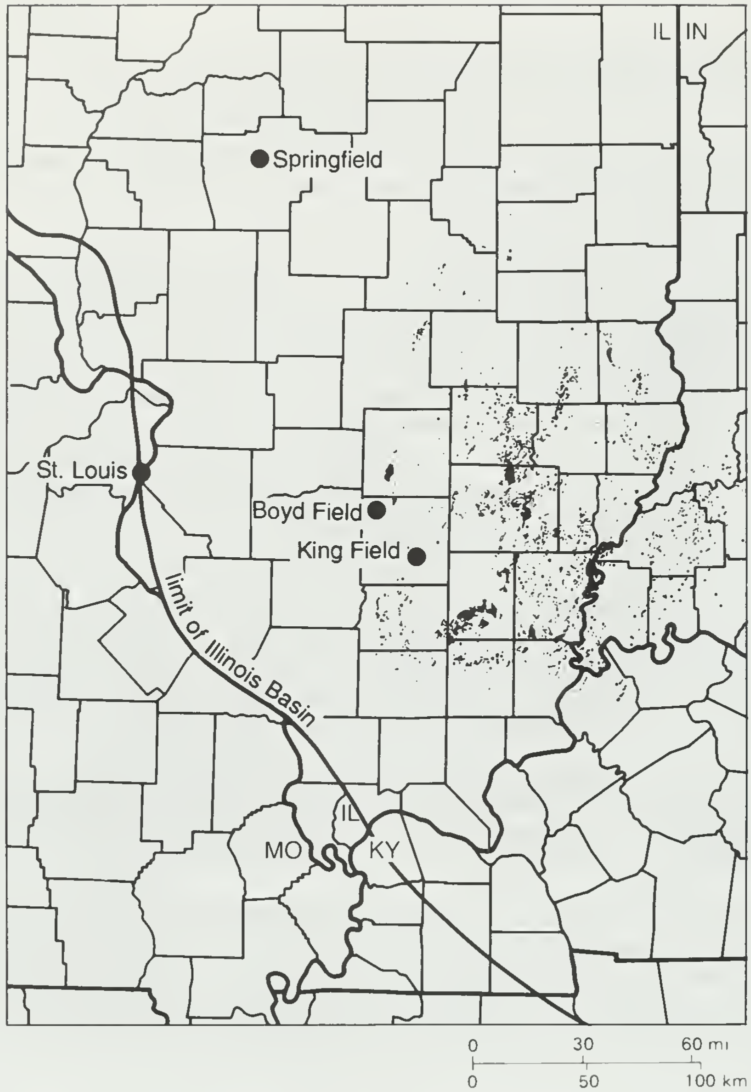


Figure 1 Regional map showing Boyd Field with respect to Aux Vases production within the Illinois Basin (after Howard 1990).

15 million barrels of oil since its discovery in 1944. By 1990 a total of 116 wells had produced oil at Boyd Field; 48 of the wells were Aux Vases producers.

Production History

The Cameron Oil Co. J.C. Bizot No. 1, drilled to a depth of 2,063 feet in 1944, was the discovery well for Boyd Field (fig. 3). The well, completed in the Benoist sandstone, produced 167 barrels of oil per day (BOPD). The first well completed in the Aux Vases sandstone occurred 4 months later, when the Superior Oil Co. P. Price No. 4 was drilled to a depth of 2,158 feet and completed open hole. This well produced 259 BOPD and less than 1 barrel of water per day (BWPD) from a depth of 2,134 to 2,157 feet.

Most wells in the field were drilled in the first 4 years following completion of the discovery well. Plots of average monthly production per year (fig. 4) and cumulative oil production (fig. 5) show significant events in the development of the field (production is from all reservoirs). From 1944 to 1953, the field produced 8.6 million

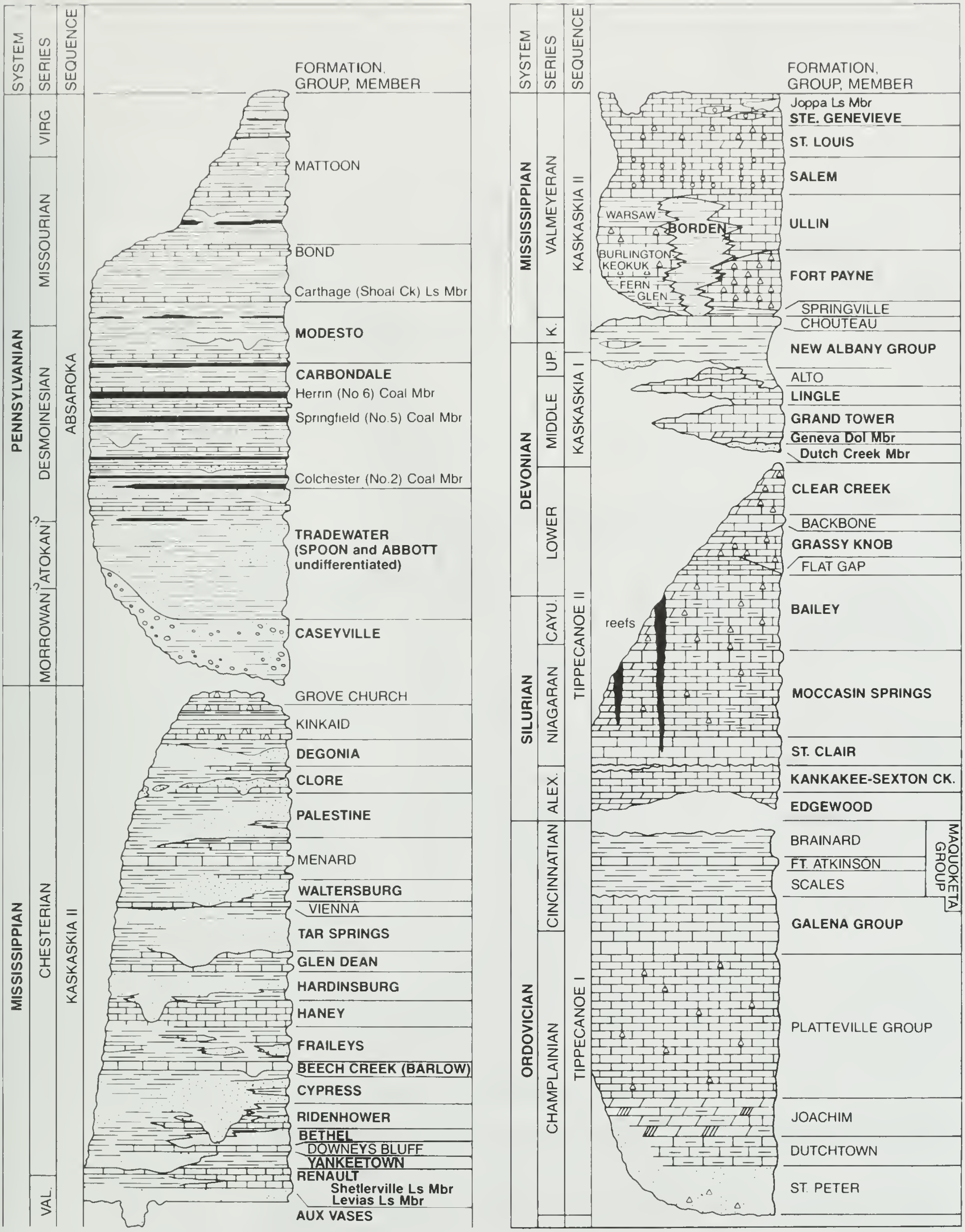


Figure 2 Generalized stratigraphic column of the Pennsylvanian through Ordovician Systems in southern Illinois (modified from Heigold and Whitaker 1989). Bold type indicates intervals that contain hydrocarbon reservoirs.

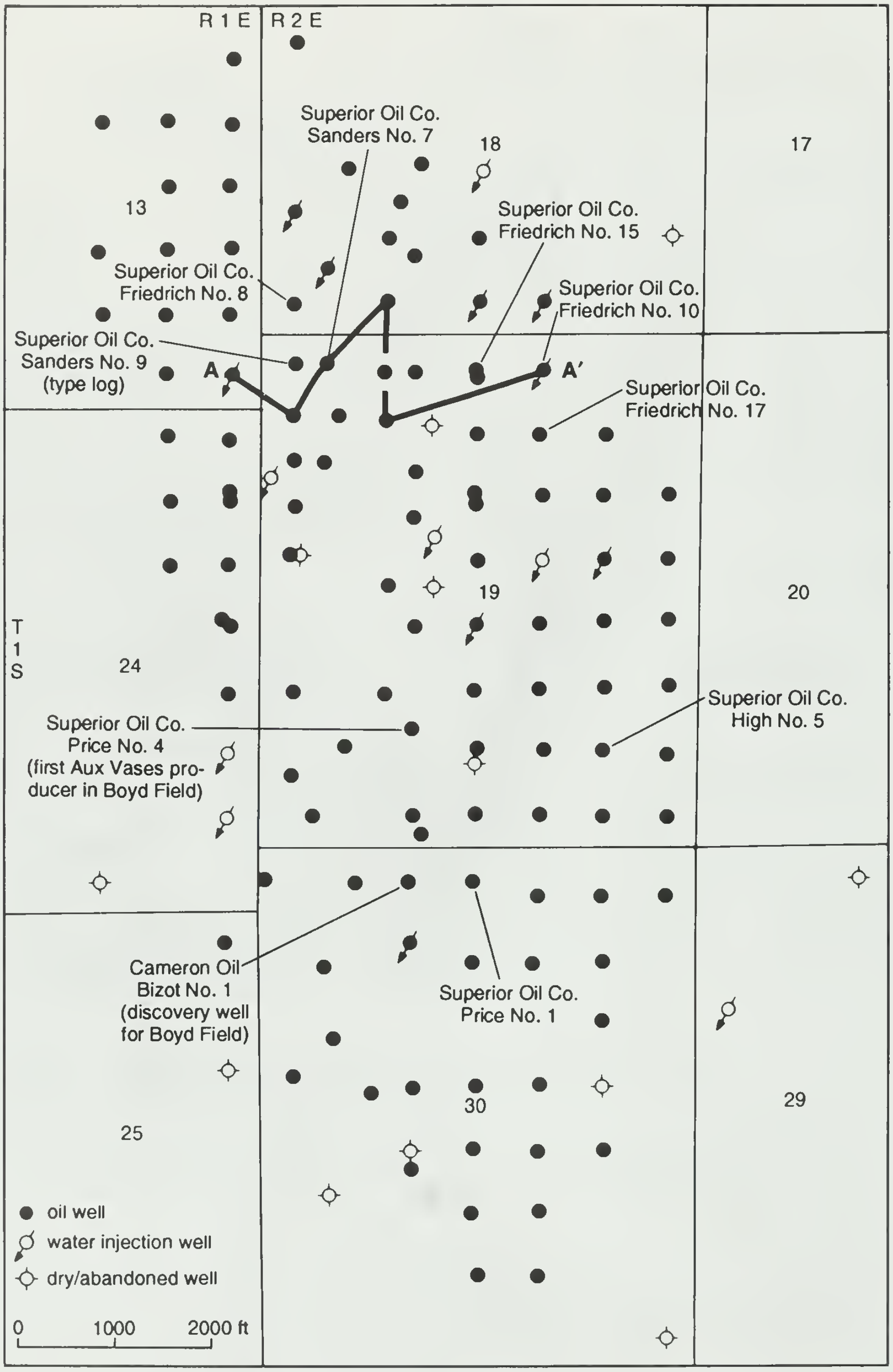


Figure 3 Base map of Boyd Field area. The location of all wells and the structural cross section referred to in this report are annotated.

barrels of oil (MMBO), with an average decline rate of 15% per year for primary recovery. In 1954, the field was unitized and several wells were converted to injection wells to waterflood both the Aux Vases and Benoist reservoirs. Waterflooding

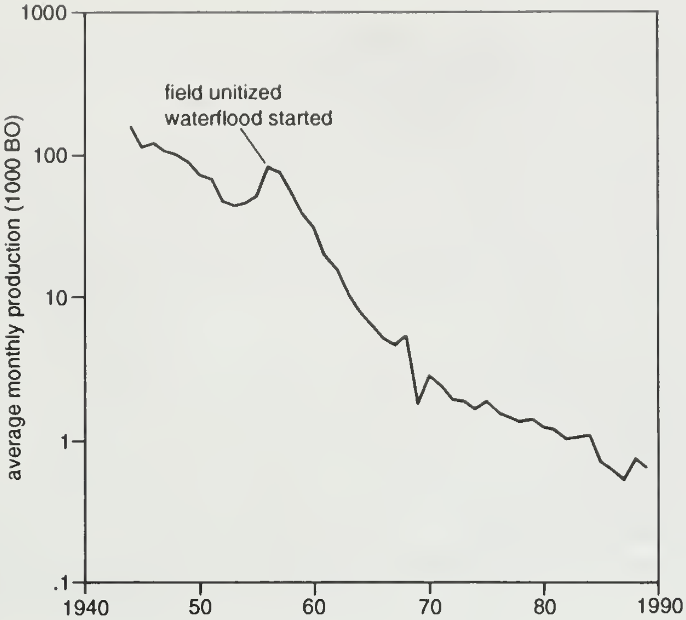


Figure 4 Decline curve of average monthly production for all reservoirs versus time (semilog scale) for Boyd Field.

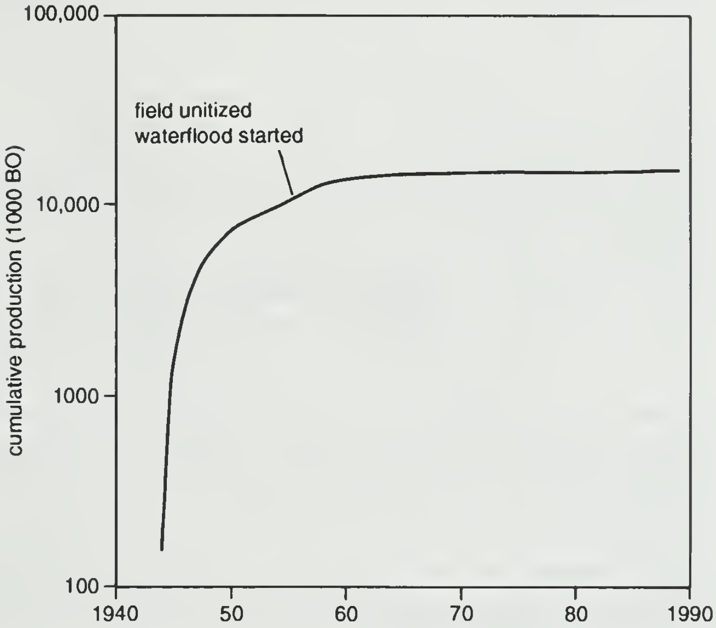


Figure 5 Cumulative oil production for all reservoirs versus time (semilog scale) for Boyd Field.

increased oil production by nearly twofold (figs. 4, 5). The brief 2 years of increased production and the subsequent increase in the decline rate to 37% suggest poor waterflood performance. By 1970, the decline rate leveled off at 7% per year. This leveling may have been caused by increasing net voidage created in the reservoir because more fluids were produced than were injected (E. O. Udegbunam, ISGS, personal communication 1993).

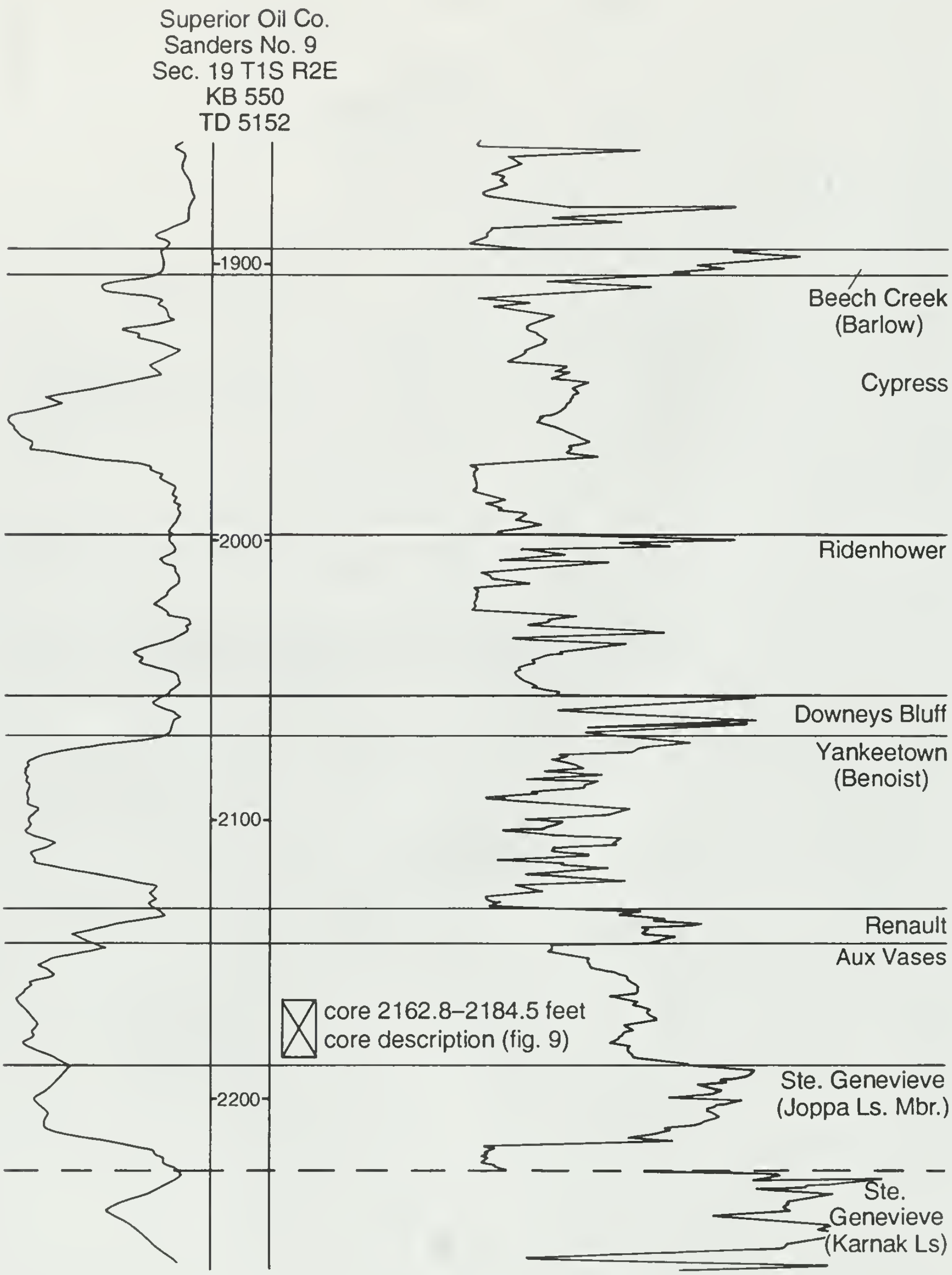


Figure 6 Type log of a portion of the Valmeyeran and Chesterian sections at Boyd Field shows key stratigraphic horizons.

RESERVOIR AND TRAP CHARACTERISTICS

General Stratigraphy

The Aux Vases Formation (fig. 6) at Boyd Field is approximately 40 feet thick, but the reservoir sandstone occurs within the upper 20 feet of the formation. Within one well spacing (660 feet), this reservoir sandstone can change into a nonpermeable siltstone or shale. Only the sandstone lithofacies is productive at Boyd Field.

The Aux Vases reservoir overlies the Joppa Limestone Member of the Ste. Genevieve Formation (Willman 1975) and underlies the carbonate-dominated Renault Formation (figs. 2, 6). The Renault is generally an impermeable brown to light reddish gray limestone that grades to a siltstone 10 to 20 feet thick. At Boyd Field, the Renault may also locally contain a thin, shaley sandstone that has a permeability of no more than 50 md (millidarcies). Recovery of hydrocarbons from this sandstone, productive in only a few areas, is generally not economical. The laterally persistent shale directly above the Renault carbonate interval is the most effective vertical seal for the Aux Vases reservoir in this field.

The base of the Benoist sandstone, 50 feet above the Aux Vases, is the principal producing horizon at Boyd Field. This sandstone, which is characterized by a "blocky" spontaneous potential (SP) log signature, is approximately 45 feet thick and continuous across a broad region within and around the field. The Benoist reservoir at Boyd Field has an average permeability of 180 md, an average porosity of 17%, and an active water drive. This drive, coupled with a relatively homogeneous reservoir, enables primary recovery to be significantly greater in the Benoist than in the compartmentalized Aux Vases reservoirs, where the drive is primarily due to gas solution (Campbell and Rickman Consultants 1954).

Structure

The principal axis of the Boyd Anticline trends generally north (fig. 7). The structure is approximately 2 1/2 miles long and 1 mile wide. The field is only 2 miles southwest of the giant Salem Consolidated Field, the formation of which was associated with a drape fold overlying one or more faults in the Precambrian crystalline basement (Nelson 1990). The Boyd Anticline may have formed in a similar fashion.

Structure is important in defining the maximum areal limits of Aux Vases production; however, local stratigraphy strongly influences the Aux Vases reservoir trapping mechanism. The structure at the top of the Benoist sandstone (fig. 7) is an anticline with about 20 feet of closure. Similar structural closure is found on top of the Aux Vases sandstone (fig. 8). The tops of the Benoist and Aux Vases reservoirs, as defined on wireline logs, are the two most easily recognized marker horizons in this stratigraphic interval. Structure maps of the two reservoirs are not identical because facies changes cause thickening or thinning of the Aux Vases Formation.

Geologic Data and Methodology

Minipermeameter Permeability was determined using a minipermeameter at 1 inch intervals on a core taken at a depth of 2,162.8 to 2,184.0 feet from the Superior Oil Co. Sanders No. 9 well (fig. 9). The core is illustrated in figure 10 and described in figure 9. The minipermeameter measures permeability quickly and accurately without destroying the core. When used on a flat rock surface, a minipermeameter provides reasonably accurate permeability measurements in the range from 10 to 500 md (Weber 1982). Observed variations in permeability measurements from closely spaced intervals may provide a more realistic picture of permeability than is obtained from traditional core measurements (Weber 1982). Minipermeameter values were slightly lower than the permeability values taken from core plugs (D. J. Haggerty, ISGS, personal communication 1993). Permeability measurements from core plugs, as measured in a gas permeameter, give an average permeability for the entire plug, whereas the minipermeameter measures a spot with a 1/4 inch diameter. Minipermeameter readings are greatly affected by minute changes in facies. For example, permeabilities are adversely influenced by sandy limestone, interlayered shale and mudstone, and sand laminae cemented with calcite.

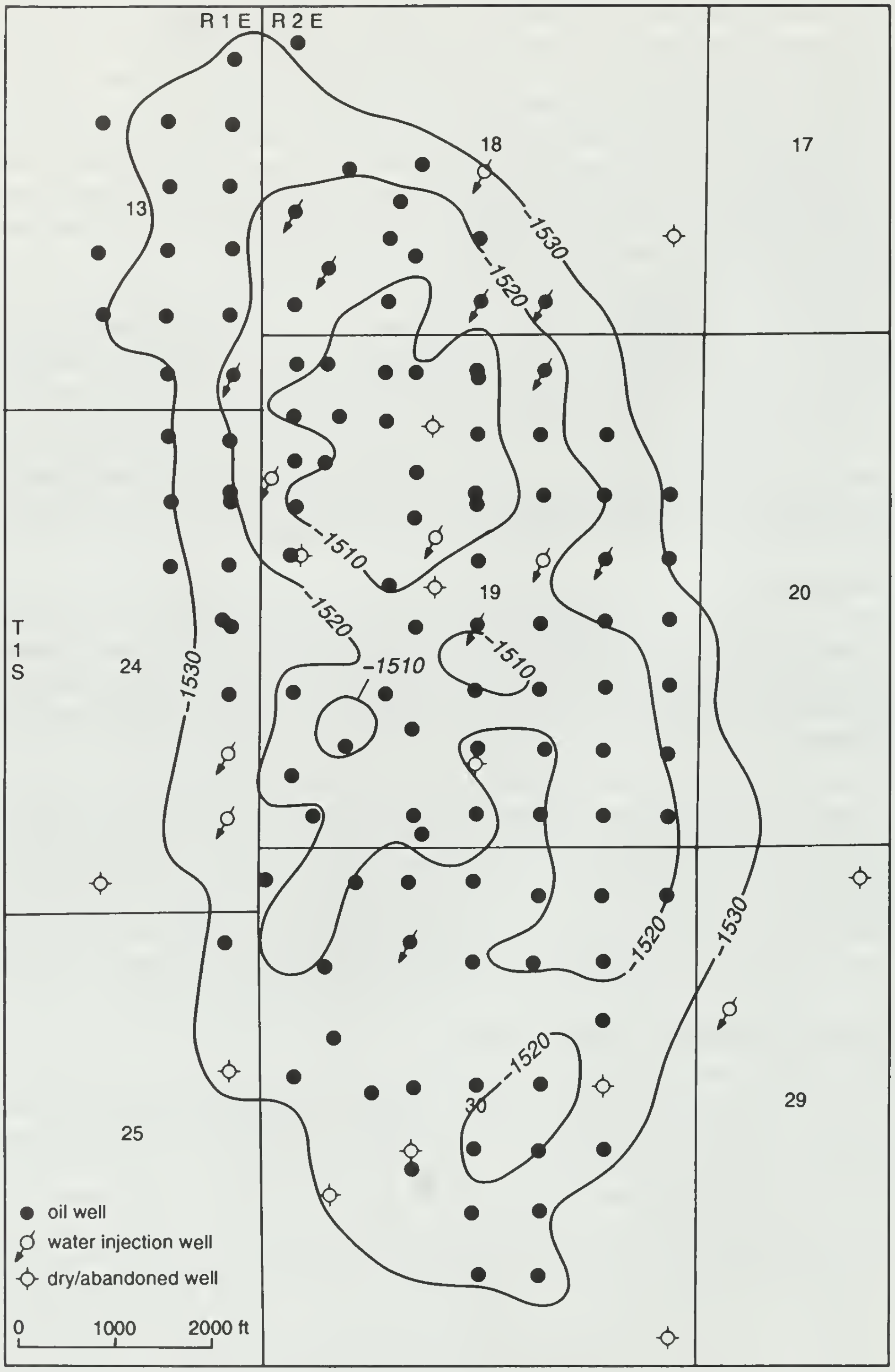


Figure 7 Structure map contoured on the top of the Benoist sandstone. Contour interval is 10 feet.

Not all variations in permeability measured by the minipermeameter are due to facies changes. For example, the sharp drop in permeability for the interval of 2,170 to 2,172 feet (fig. 9) probably was not directly related to facies changes. This interval

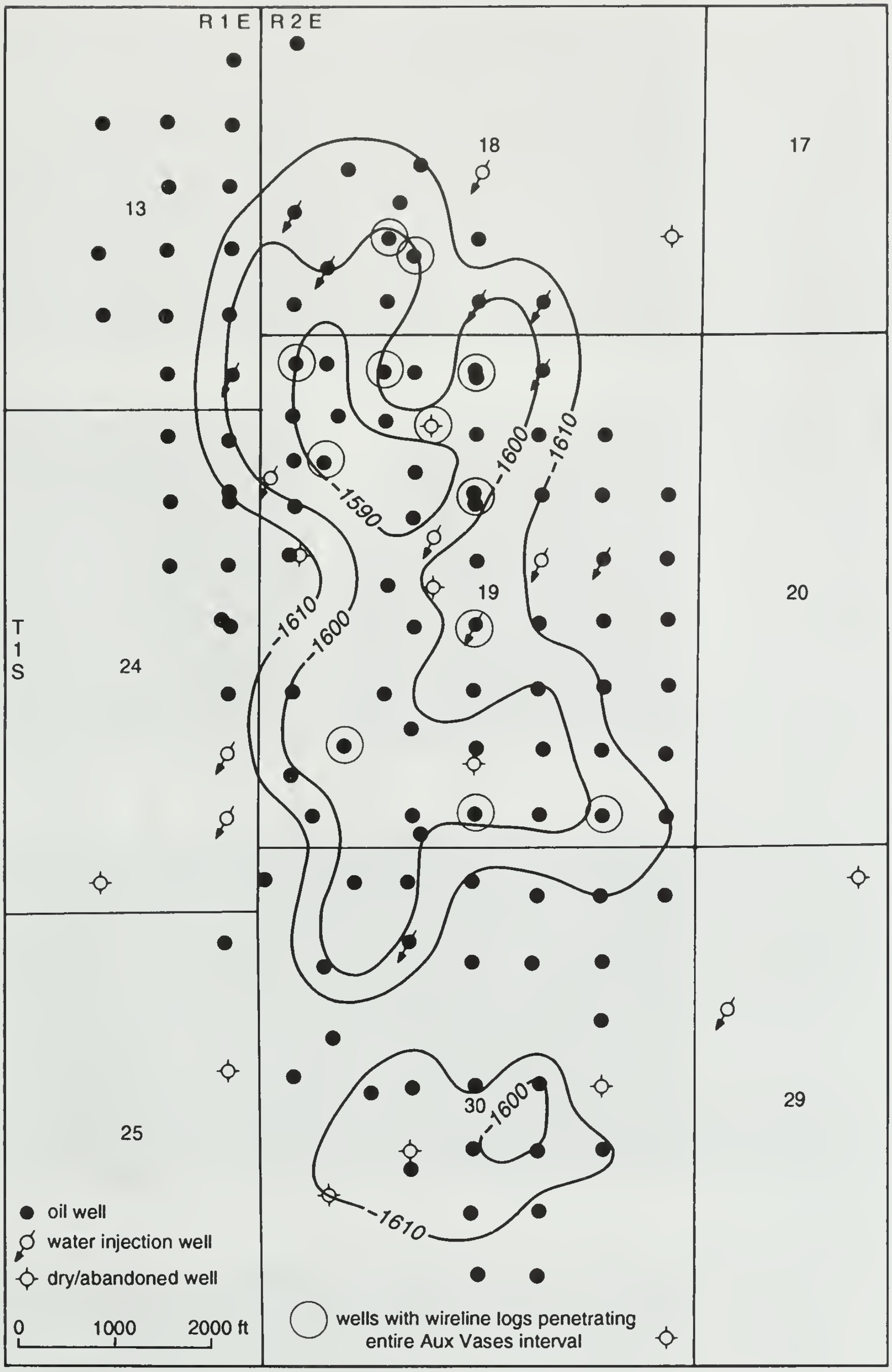
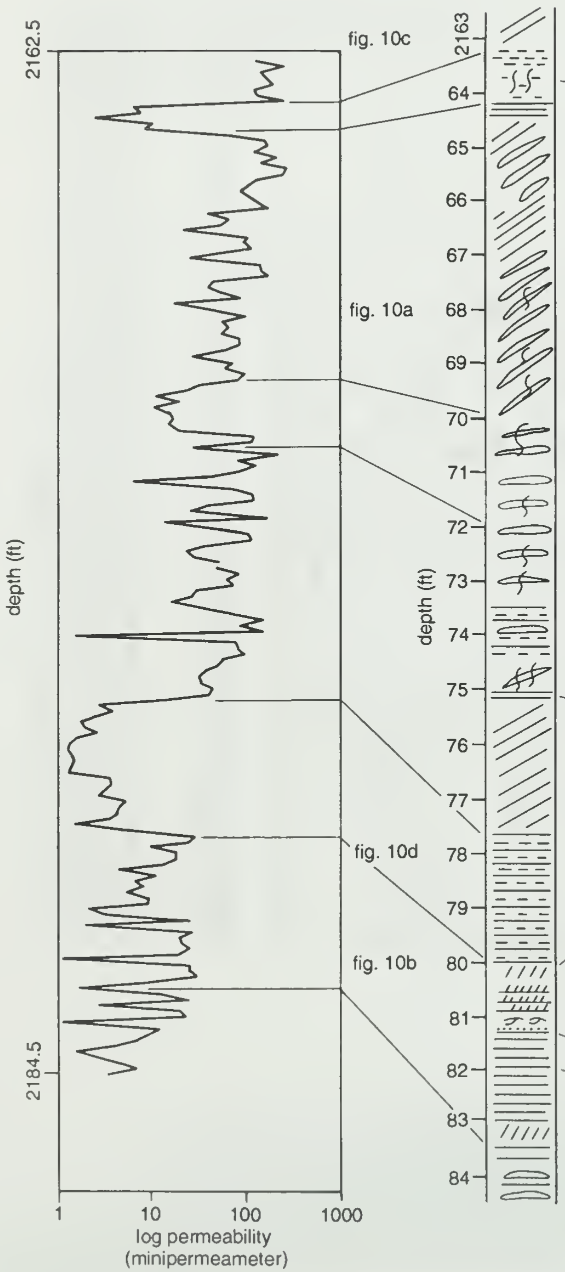


Figure 8 Structure map contoured on the top of the Aux Vases reservoir sandstone. Contour interval is 10 feet.

was infused with an inordinate amount of drilling mud because this portion of the core had apparently been unsuccessfully cleaned. Thus, it seems likely that the mud effectively blocked accurate measurement of permeability and that this zone actually has higher permeabilities than the measured values.



Description	Interpretation
Cross laminae; fine grained sandstone; burrowing slight or absent	Moderate current velocity with medium scale bed forms
1 inch thick laminated green shale	Low energy environment; very low level of burrowing
Mixture of green shale and fine grained sandstone completely burrowed	Relatively low energy; dense in fauna
Cross laminae with calcite cement along set boundaries	Intermediate current velocity; medium scale bed forms
Cross laminae, less calcite	Carbonate cement may have been precipitated preferentially along minute grain-size changes at bedding planes; or these calcite zones had higher concentrations of calcite
Cross laminae with calcite cement along set boundaries	Low levels of burrowing suggest fairly rapid sedimentation
Planar laminated to slightly cross laminated (increase in burrowing)	
Rhythmites; thinly interlayered sandstone/shale calcite cemented intervals	Regular changes of short duration such as current fluctuations due to tides; rhythmites have less shale than those immediately above, indicating mud size sediment may not be as abundant
Cross laminae with calcite cement along set boundaries	
Cross laminae	
Dead oil on some laminae	
Rhythmites; thinly interlayered sandstone/shale	Regular changes of short duration such as current fluctuations due to tides
Cross laminated sandy limestone; some ooids	Presence of ooids and abundant calcite cement suggest penecontemporaneous deposition of siliciclastics and carbonates
Small ripple bedding	Low to moderate energy with variable current velocity; low levels of burrowing suggest high sediment influx or continual wave or current reworking
Wave ripple bedding, some flaser or clay drape (burrowing slight to absent)	
Graded bedding	Graded beds were the result of deposition by waning current
Planar laminae sand (burrowing slight to absent); planar cross laminae; disseminated calcite throughout	
Planar laminae with interbedded extremely fossiliferous cross laminae zones	Presence of ooids and abundant calcite cement suggest penecontemporaneous deposition of siliciclastics and carbonates

Figure 9 Core description and minipermeameter readings of the Aux Vases interval in the Superior Oil Co. Sanders No. 9 well. All depths that refer to this core are keyed to the depth next to the core description. The depth scale readings shown next to the minipermeameter reading are approximate. The core is illustrated in figure 10.

Figure 9 explanation

cross laminae

shale

cross laminae with calcite cement along laminae boundaries

burrows

small ripple bedding

planar laminae

rhythmites

wave ripple bedding

0 1 in.

Figure 10a A clean laminated sandstone. The cross laminae are cemented with calcite along the laminae boundaries. The sample is from the Sanders No. 9 well (depth 2,168 ft).

Figure 10b Extremely fossiliferous, cross laminated, sandy limestone. The shale clasts have a tendency to expand when exposed to freshwater. The sample is from the Sanders No. 9 well (depth 2,180 ft).

Figure 10c The lower core is a heavily bioturbated sand and shale mixture that is capped by a well laminated, green shale. The upper core is a clean, cross laminated sandstone. The sample is from Sanders No. 9 well (depth 2,163 ft).

Figure 10d Thinly interlaminated sequence of sandstone and mudstone. The sand-mud couplets are interpreted to be tidal rhythmite deposits that formed during the flood-ebb tidal cycles. Sample is from the Sanders No. 9 well (depth 2,178 ft).

During a secondary or tertiary recovery program, abrupt variations in permeability may decrease the recovery efficiency. Fluids will bypass the lower permeability zones, leaving recoverable mobile oil in the pore spaces. An enhanced oil recovery program must take into account the types of permeability variations illustrated by the core from the Sanders No. 9 well.

Petrographic methods Observed variations in texture and lithology, as well as physical and biogenic structures, in the core from the Superior Oil Co. Sanders No. 9 well were used to differentiate various facies of the Aux Vases Formation for the interval of 2,162.8 to 2,184.5 feet. Five petrographic thin sections were cut from the Sanders No. 9 core, and 10 additional thin sections of the Aux Vases were made from core-sized biscuits from the Superior Oil Co. Price No. 1, Sanders No. 7, and High No. 5 wells (fig. 3). Samples also were analyzed using scanning electron microscopy (SEM), energy dispersive X-ray (EDX), and X-ray diffraction (XRD).

Interpretation of the depositional lithofacies was strongly influenced by the whole core from the Sanders No. 9 well. Although this core was recovered from a zone a few feet below the producing Aux Vases zones, comparisons of wireline log patterns, thin sections, whole core, and core biscuits suggest that lithologies observed in the whole core and their interpreted depositional environments are similar to those of the shallower Aux Vases producing zones.

Lithofacies from electric logs The various lithologies within the Aux Vases Formation were differentiated primarily by their electric log responses. Porosity and permeability measurements are available from 26 of the wells, although the cores from which they were taken have long since been discarded. Most wells penetrated only the top 20 feet of the Aux Vases Formation; only 12 wells penetrated the entire formation (fig. 8). This study concentrated on the upper 20 feet of the formation where the production occurs; the lack of deeper Aux Vases wells was not considered detrimental in evaluating this reservoir.

The clean, thick sandstones of the Cypress and the Benoist Formations have a consistently high SP deflection and were used to define the 100% sand value on the SP curve. The shale baseline value was defined by the shales directly above the Renault Formation. Zones in the Aux Vases Formation that have SP measurements greater than 50% of SP measurements of the Cypress or Benoist Formation, and resistivities of less than 40 ohm-m, were considered to be sandstone lithologies. Intervals on the wireline log have resistivities greater than 40 ohm-m and are considered to be calcareous zones; however, older resistivity tools will not detect beds thinner than 16 inches. Sand thickness was calculated by measuring the cumulative thickness of sandstones showing greater than 50% SP deflection from the shale baseline. Aux Vases sandstone bodies with high SP deflections generally have high permeabilities and porosities and are the best reservoirs (Leetaru 1991). Siltstones or shaley sandstones have SP deflections less than 50% and resistivities less than 5 ohm-m.

Depositional Facies

During Aux Vases deposition, the Illinois Basin was a shallow intracratonic basin with no evidence of deep water deposition in either the outcrop (Cole 1990) or the subsurface (Swann and Bell 1958). Paleocurrent direction data and gross sandstone isopachs suggest that the dominant source region for the sandstones of the Aux Vases was to the northwest or west (Potter et al. 1958).

This report follows the definition of nearshore of Campbell (1979) and Pettijohn et al. (1987). Nearshore extends from the upper limit of storm tides to the seaward limit of sand deposition. Environments of the nearshore zone range from the subaerial

to brackish and shallow marine. In modern environments, the nearshore zone may be up to several miles wide. In the intracratonic Illinois basin, however, depositional gradients were extremely low and the nearshore environment may have been tens of miles wide. With such a low gradient, small changes in sea level could have caused significant shifts in the relative positions of subenvironments (Laporte 1967).

The broad nearshore environment suggests that the Aux Vases at Boyd Field may include lithofacies deposited in several subenvironments, including marine offshore sandstones and tidal flat shales. The upper 20 feet of the Aux Vases is composed of two different lithofacies—sandstone containing some intercalated calcareous lithologies, and siltstone and shale. The sandstone lithofacies forms the most productive reservoir at Boyd Field.

Sandstone facies The reservoir sandstone is classified as a quartz arenite grading to subarkose. Analyses of selected samples by XRD (appendix A) and estimates of mineral percentages from thin sections of other samples indicate that the reservoir sandstone contains 80% quartz and less than 10% feldspar. The XRD analyses of the samples consistently showed more potassium feldspar than plagioclase feldspar. The difference in relative abundance of the two minerals is probably due to selective dissolution of plagioclase feldspar.

The sandstone is cemented by calcite, silica in the form of quartz overgrowths, and clay minerals. The amount of calcite in reservoir-quality rock ranges from 1% to 28%. Sporadic disseminated patches of calcite cement have nucleated around fossil fragments. The best reservoir sandstones have clay minerals as the dominant cement and are extremely friable. Individual sand grains can be easily dislodged in hand specimens of these rocks. In less friable, lower quality reservoir sandstones, clay minerals are less abundant and the cements are mostly calcite and silica.

Within the sandstone reservoir are numerous calcareous-rich zones. Most of the calcareous zones occur as thin laminations (<0.2 inches thick) (fig. 9) of limited lateral extent. These thin calcareous zones formed where concentrations of calcite cement precipitated preferentially along the boundaries of laminae sets (figure 10a). Calcite cementation was probably controlled by minute grain-size changes in the laminae and by concentrations of carbonate detritus in the laminae. Shell lags formed by the winnowing action of waves may have concentrated the carbonate detritus in these laminae. Similar shell lags can be found in modern nearshore marine depositional systems. Thin section analysis shows that only small amounts (<10%) of calcite occur as disseminated cement filling pore spaces.

Calcareous-rich zones occur not only as bed set laminae, but also as thicker, sandy cross laminated limestones. These sandy limestones contain fossil fragments, ooids, and shale clasts that suggest high energy transport from nearby areas (fig. 10b). This type of calcareous interval may be laterally extensive, especially if it was deposited as a result of storm surge into an otherwise siliciclastic depositional system.

A contour map of the distribution of reservoir-quality sand in the upper 20 feet of the formation shows sandstone bodies elongated north–south (fig. 11). The map suggests the existence of at least four lateral compartments, labeled B1, B2, B3, and B4. The southernmost of the compartments, B4, located in Section 30, was not contoured because the wells only penetrated the top of the formation. Evidence that some of these compartments are separate reservoirs not in communication with each other is based primarily on the elevation of the original oil–water contact. Compartments B1 and B2 have a poorly defined oil–water contact at –1,615 feet. The depth of the oil–water contact is not precise because the cored wells rarely

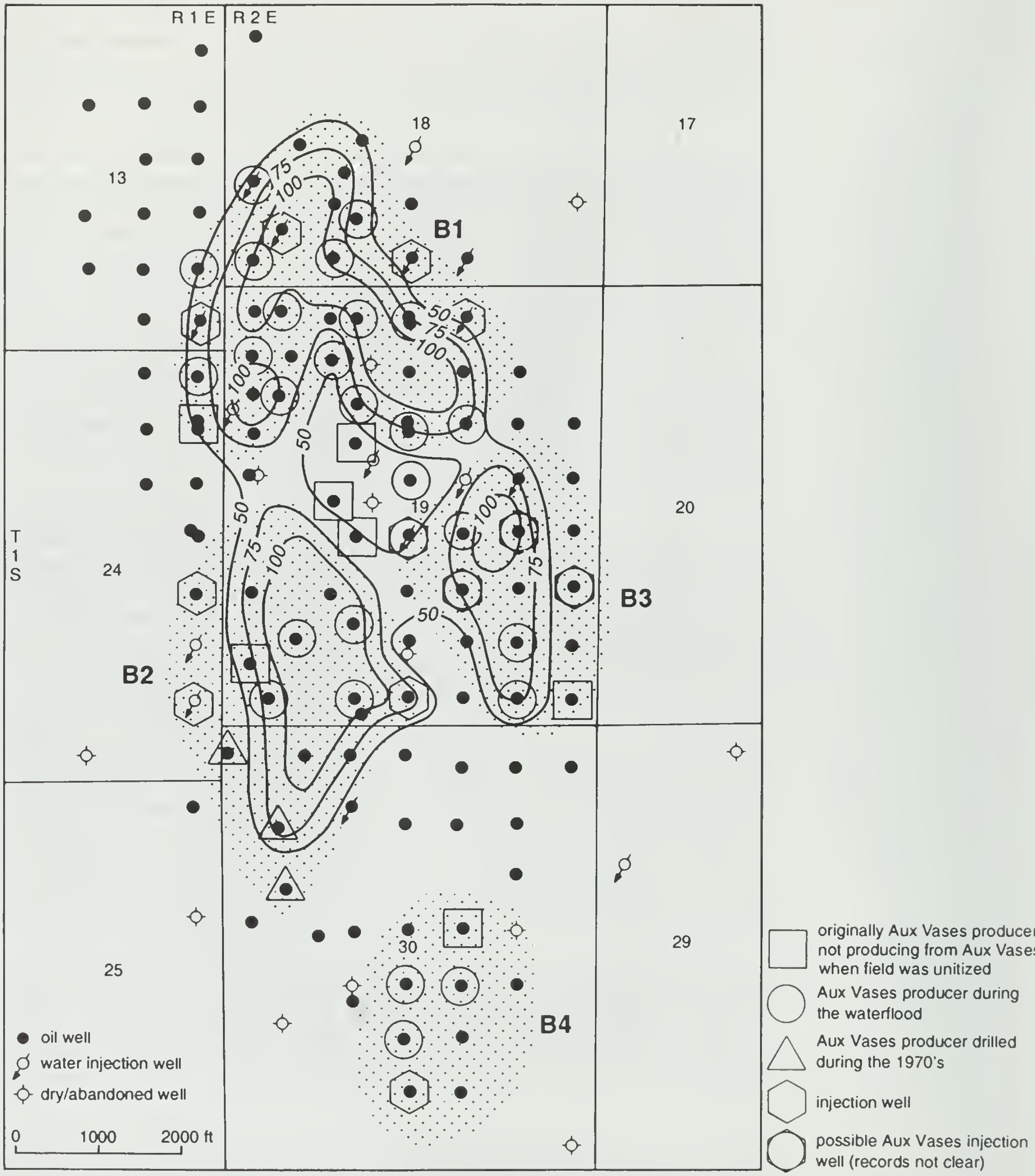


Figure 11 Contour map of percentage of clean Aux Vases sandstone in the upper 20 feet of the formation. A clean sandstone is defined as having an SP response that is at least 50% of the SP response of clean, thick Cypress or Benoist sandstone. The stippled pattern highlights the four lateral reservoir compartments. Contour interval is 25%.

penetrated this contact and old wireline logs do not accurately measure water saturations in the Aux Vases reservoir. Compartment B3 had an original oil–water contact at –1,623 feet. Since none of the wells penetrated the oil–water contact in compartment B4, the original elevation of the oil–water contact is unknown. Compartment B4 is more than 1/2 mile from the other compartments, however, and probably has its own oil–water contact. The variations in oil–water contact elevations indicate that at least three of the four compartments are not in communication with each other. The compartments probably are separated by siltstones, shales, and mudstones, all of which represent distinct facies in the Aux Vases.

Siltstone and shale facies The siltstone and shale facies, which also includes mudstone, is generally light green and has no effective porosity or permeability. The siltstone and shale facies forms effective vertical and lateral barriers to fluid flow, and plays a major role in reservoir heterogeneity. In places, beds representing this facies have a lateral continuity of more than two 10 acre well spacings (a distance greater than 1,320 feet), thereby compartmentalizing the reservoir sandstone. The siltstone and shale facies is not productive at Boyd Field.

As indicated by the Sanders No. 9 core, the siltstone and shale facies formed in two different depositional settings. The interval (fig. 9) from 2,163.5 to 2,164.3 feet (fig. 10c) consists of a heavily bioturbated sand–shale mixture capped by a laminated green shale. The large degree of bioturbation suggests deposition in a low energy environment such as a tidal mud flat. The laminated green shale is extremely fissile and swells when in contact with freshwater. Strong laminations suggest that this part of the sediment was not heavily burrowed. The reason for the lack of burrowing in this zone is uncertain. This lower core (figure 10c) had less than 10 md permeability (minipermeameter). The upper core had a permeability of 168 md, as measured by minipermeameter, and 357 md, as measured in a core plug by gas permeameter. The contact between the two core halves, interpreted to be erosional, increases vertical heterogeneity.

The second type of depositional setting for the siltstone and shale facies, represented by an interval of 2,177.8 to 2,180 feet, is the lower permeability zone in the core from the Sanders No. 9 well (fig. 9). Similar interlayered sandstone–mudstone (rhythmite) intervals (fig. 10d) typically form in tidally influenced systems (Reinek and Singh 1980, Nio and Yang 1991). The sandstones of this rhythmite interval were deposited during flood and ebb tides; the mudstones were deposited during the stillstand phases at high and low water.

DIAGENESIS AND ITS EFFECT ON RESERVOIR QUALITY

Most of the samples examined contain three types of cement: silica in the form of quartz overgrowths, clay minerals, and calcite. These diagenetically formed minerals modified the original permeability and porosity of the reservoir in both detrimental and positive ways. For example, at Boyd Field, silica cement in the form of quartz overgrowths occluded primary porosity. Porosity rapidly decreases as silica cement increases because, unlike clay minerals, quartz grains do not contain micropores.

Clay minerals, identified by XRD analyses, constitute less than 5% of bulk volume (modal analyses of clay and other minerals are in appendix A). These clay mineral suites consist of illite, mixed-layered illite/smectite, and chlorite in various proportions. The XRD analyses indicate that a large percentage of the diagenetic clay minerals in the more porous facies are a form of iron-rich chlorite (R. E. Hughes, ISGS, personal communication 1993). SEM photomicrographs show that the most productive Aux Vases reservoir rock has a relatively continuous dusting of clay mineral around each quartz grain. Such continuous clay mineral coatings have been

shown to inhibit the formation of quartz cement in other reservoirs (Pittman and Lumsden 1968, Thomson 1982).

Petrographic analyses showed that diagenetic clay minerals representing both early and late diagenetic events are a result of feldspar dissolution and migration of fluids from nearby shales. One of the first diagenetic events to have a positive effect on reservoir quality was the early formation of grain-coating clay minerals. Later diagenetic clay minerals occluded the original porosity and decreased permeability by clogging the pore throats. Most of these diagenetic clay minerals have significant amounts of microporosity. The role of the clay minerals in hydrocarbon production is discussed later.

The effect of carbonate minerals on reservoir quality at Boyd Field is ambiguous. Calcite cement has filled some of the primary porosity and has an irregular distribution. Calcite may also have replaced some framework grains. Although dissolution of calcite appears to have resulted in some porosity enhancement, the actual amount of this dissolution is unknown. Two types of calcite cement, defined by the presence or absence of iron, are in the Aux Vases at Boyd Field. All thin sections were dyed with Alizarin Red-S to identify calcite and potassium ferricyanide to distinguish iron-bearing calcite. Type I (low iron) calcite cement, which apparently precipitated around whole and fragmented echinoderm grains, is usually interpreted to have formed early in the diagenetic sequence (Bathurst 1975). Type II (ferroan) calcite cement is a euhedral ferroan variety that was shown in other areas to form late in the diagenetic sequence (Surdam et al. 1989). At Boyd Field, this ferroan calcite cement generally nucleated around the earlier type I cements.

Porosity in the reservoir lithofacies is predominantly intergranular with small amounts of intragranular porosity. Intergranular porosity results from preservation of primary pore space and dissolution of feldspar grains and secondary calcium carbonate cement. Intragranular porosity, which results principally from dissolution of feldspar grains, begins with the formation of micropores. In more advanced stages, the micropores join to form larger pores characterized by a honeycomb appearance.

Sandstones in the Aux Vases reservoir at Boyd Field have undergone a complex diagenetic history. The major events in approximate order of occurrence are as follows:

- precipitation of low-iron calcite cement around fossil fragments, especially echinoderms;
- formation of diagenetic clay minerals;
- formation of minor quartz overgrowth;
- dissolution of feldspars;
- second stage of diagenetic clay mineral formation and ferroan calcite cementation;
- migration of hydrocarbons into the reservoir. Hydrocarbons usually freeze the diagenetic processes because no further brine flows through the formation.

FACIES ARCHITECTURE AND RESERVOIR CONTINUITY

Comparisons between Boyd Field and King Field (Leetaru 1991) are useful because they are only 10 miles apart and are in a similar depositional system. Both fields also produce from the Aux Vases, yet they have a different facies architecture. The producing interval of the Aux Vases Formation at both fields occurs within the upper 30 feet of the formation, and was deposited in a nearshore marine environment of

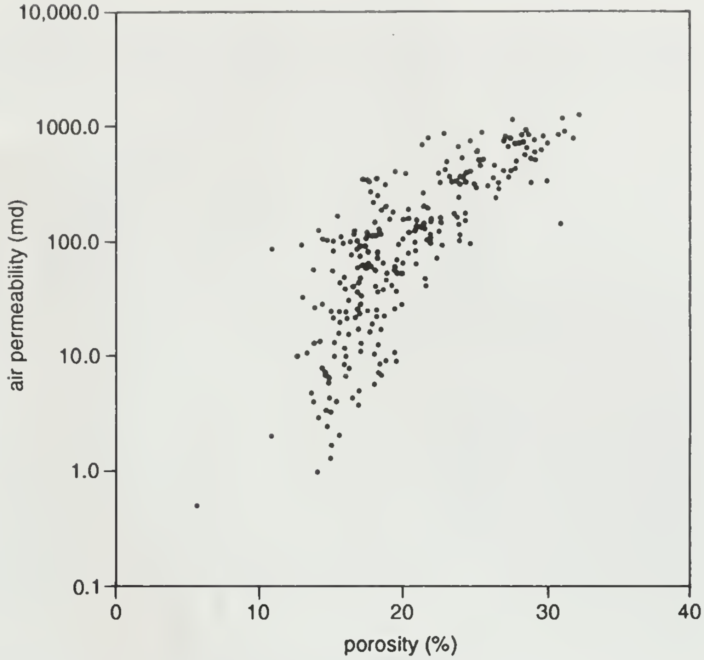


Figure 12 Plot of Boyd Field Aux Vases sandstone porosity versus permeability measurements determined from core plugs.

mixed carbonate–clastic sediments. The well control suggests that the producing interval at Boyd Field was not dominated by carbonates to the same degree as the producing interval at King Field. This relationship suggests that Boyd Field may have been closer to a source of clastic sediments than King Field. Other differences also exist. The calcareous lithofacies and the siltstone and shale facies at King are impermeable barriers to fluid flow. At Boyd, the calcareous lithofacies is not a significant factor in reservoir compartmentalization because it is not present in appreciable amounts.

As will be shown, the Aux Vases deposition at Boyd Field resulted in a heterogeneous reservoir comprising an intercalated sequence of sandstones, siltstones, shales, mudstones, and carbonates. This complex facies mosaic makes it difficult to define the true limits of the Aux Vases reservoir. The lateral discontinuities that separate the Aux Vases sandstone at Boyd Field into four separate compartments are a critical consideration during design of a waterflood.

Permeability in the Aux Vases reservoir ranges from a low of 1 md to a high of more than 1 d (fig. 12). Cross section A–A′ (fig. 13) shows variations of measured core permeability within the Aux Vases reservoir in compartment B1. In this cross section, the Aux Vases sandstone has a range of permeabilities from less than 1 md to 800 md. The reservoir along this cross section was subdivided into three flow units of similar permeability values. A flow unit is “a volume of the total reservoir rock within which geological and petrophysical properties that affect fluid flow are internally consistent and predictably different from the properties of other volumes, i.e. flow units” (Ebanks 1978). The flow units in this cross section are above the proposed oil–water contact at –1,615 feet; the unit directly below the base of the Renault Limestone is an impermeable shale or siltstone. The most permeable units are the upper A and B, where permeabilities exceed 600 md (fig. 13). The A and B units are separated by a relatively less permeable zone that impedes flow between them. The upper A and B units become impermeable siltstones and shales in the west

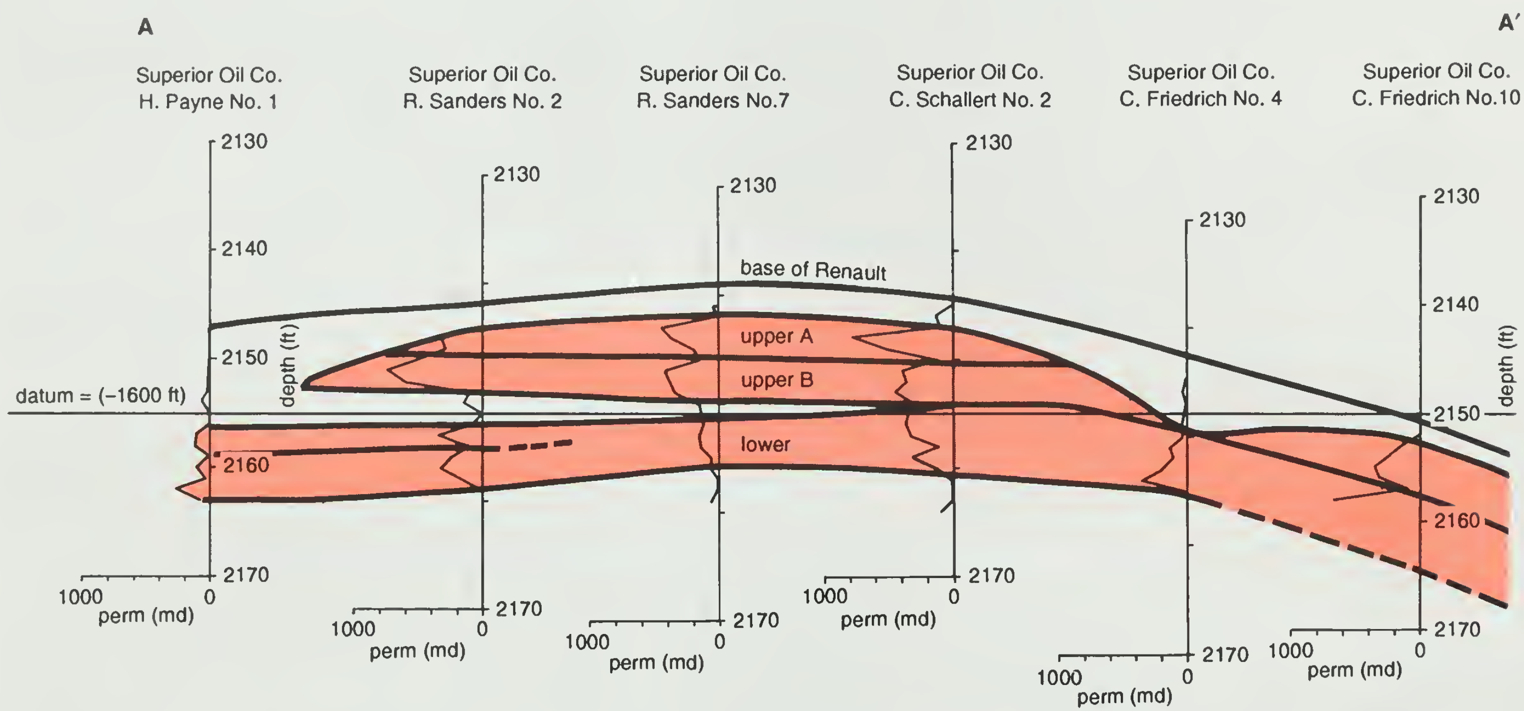


Figure 13 Cross section A–A′. This section through compartment B1 shows flow units as defined by permeability variations within the Aux Vases sandstone. (Location of the cross section is shown on fig. 3.)

and south part of the reservoir. In the two central wells, Sanders No. 7 and Schallert No. 2, the lower and upper flow units are not separated; however, in the other wells on this cross section, a laterally continuous shale locally compartmentalizes the Aux Vases sandstone.

PRODUCTION CHARACTERISTICS

Drilling and Completion Practices

Nearly all wells at Boyd Field were drilled with a bentonite slurry laden with drill cuttings suspended in freshwater. Most wells in the field that produce from the Aux Vases were completed open hole with the casing set slightly above the Aux Vases Formation. These wells were each fractured with between 10 and 80 quarts of nitroglycerin. Wells completed in the Benoist were generally treated with no more than 8 quarts of nitroglycerin. Most wells that produce from the Aux Vases Formation also are perforated in the Benoist sandstone; therefore, production was commingled, precluding accurate Aux Vases production records. At the time of this report, only three wells still produced from the Aux Vases Formation; the others produced from only the Benoist Formation (David Sheridan, Bi-Petro Corporation, personal communication 1993).

DEVELOPMENT AND PRODUCTION STRATEGIES

Case Histories

Boyd Field was unitized in 1954 and production from both formations was increased by the water injection program instituted at that time. The Benoist sandstone, the base of which is less than 50 feet above the Aux Vases reservoir, was the principal target during development of Boyd Field. The Benoist is a water drive reservoir, whereas the Aux Vases has a combination of solution gas and weak water drive. This difference in drive mechanisms is of critical importance to recovery efficiency in the Aux Vases because production from the Benoist and Aux Vases reservoirs was commingled. Not only does the Benoist have a greater reservoir efficiency, but its reservoir pressure decline is also much slower. After a few years of commingled production, the higher reservoir pressure of the Benoist inhibited or stopped fluid flow from the Aux Vases. Backflow from the Benoist into the Aux Vases has probably occurred. In this report, four wells are used to illustrate the problems that commingling of the two reservoirs may have had on production. The locations of these four wells are shown on figure 3.

In April 1956, a packer was used to isolate the Aux Vases production in the Superior Oil Co. Friedrich No. 15 well, a dual Benoist and Aux Vases producer. After the packer was set, oil production increased nearly five-fold, from 3.4 to 16 BOPD (fig. 14). The amount of produced water decreased from 98% to 68%. The significant increase in production after the Aux Vases was isolated implies that Aux Vases production was impeded by the higher pressure flow of reservoir fluids from the Benoist. The Friedrich No. 15 should have produced water from the Aux Vases because it was only 660 feet from an Aux Vases injection well, the Superior Oil Co. Friedrich No. 10. The Friedrich No. 10 was used to inject more than 200,000 barrels of water into the Aux Vases during a 2-year period. The possible water breakthrough, shown by increased water production during the 36th month, implies that either a permeability barrier existed between these two wells or that the injected water was not going into the Aux Vases reservoir. The injected water could instead have entered the Benoist reservoir through upward leakage behind the casing. Campbell and Rickman (1954) reported difficulties in obtaining good cement jobs. Strong

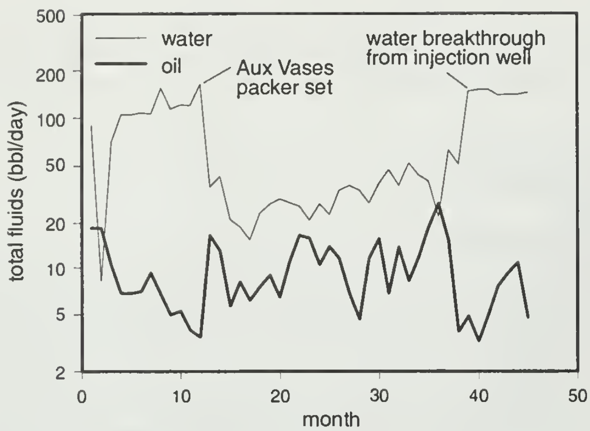


Figure 14 Average daily fluid production for each month versus time for the Superior Oil Co. Friedrich No. 15 well. The first month is May 1955.

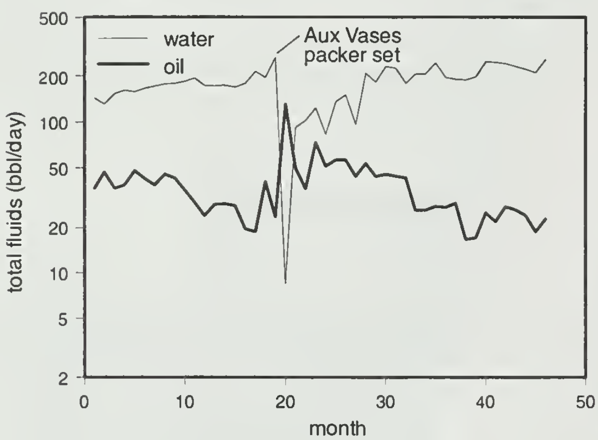


Figure 15 Average daily fluid production for each month versus time for the Superior Oil Co. High No. 5 well. The first month is May 1955.

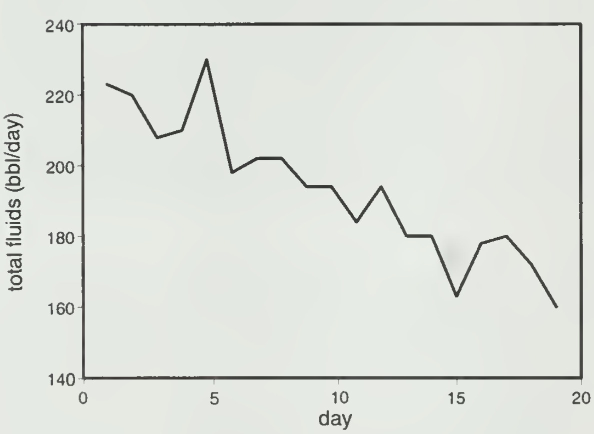


Figure 16 Average daily fluid production for the Superior Oil Co. Friedrich No. 8 well. The first day is October 9, 1960.

communication between the two reservoirs probably exists because of completion practices. Although a completion record was not available for the Friedrich No. 10, most wells in Boyd Field were treated with nitroglycerin, which shattered the rock and could easily have weakened and fractured the 50 feet of limestone and shales separating the two formations.

The Superior Oil Co. High No. 5 well had an even more dramatic increase in production when the Aux Vases was isolated after 10 years of commingled production. Production surged from an average 23 BOPD to 131 BOPD (fig. 15) and stabilized at 50 BOPD during the following months. The proportion of produced water

dropped from 86% to 65% of total fluid flow. It took 1 1/2 years for water production to return to values before packer installation.

Other wells also have achieved higher recovery rates when the Aux Vases Formation was isolated from the Benoist. Some wells, however, such as the Superior Oil Co. Friedrich Nos. 1 and 7, had no change in production when either the Benoist or the Aux Vases was isolated. This lack of response can be explained by either of two alternatives. First, the two formations may have identical producing characteristics in this geographic area. Second, and more likely, communication between the two reservoirs, as in Friedrich No. 15, could be continuing because of a poor packer seal or leakage behind the casing.

In the early 1960s, Superior Oil Company again started isolating the producing zones. During the initial completion of the Superior Oil Co. Friedrich No. 8 well in 1945, production was established first in the Benoist followed by the Aux Vases. The Aux Vases oil production added approximately 100 BOPD. In 1960, 15 years after the original completion, the operator of the field reentered the Friedrich No. 8 and ran a packer test on the Aux Vases (fig. 16). The packer test had flow rates as high as 230 barrels of fluid per day (BFPD). The total water cut was 92% of the fluid flow; however, Superior Oil Company believed that the packer leaked throughout the test and the actual Aux Vases water cut was estimated to be 82% to 83%. Within 19 days, the flow rates had declined 27%, from 220 to 160 BFPD. The estimated oil production went from 18 to 13 BOPD (fig. 16). The high flow rates and the extremely high decline rates suggested that the higher pressure Benoist reservoir had inhibited production from the Aux Vases. After 15 years, the Aux Vases production already should have declined to some steady state. Since most of the wells have commingled Aux Vases and Benoist production, the existence of additional producible reserves in the Aux Vases is highly probable.

Recommendation for Workovers, Infill Drilling, and Waterflooding

Significant amounts of recoverable oil probably remain in the Aux Vases reservoir at Boyd Field. Since it was a secondary target, the Aux Vases was ineffectively waterflooded. Several wells penetrated only the top 5 feet of the Aux Vases. As shown in cross section A–A′ (fig. 13), the Aux Vases reservoir is composed of at least three major flow units. The lower Aux Vases flow units cannot be properly drained nor can they be properly waterflooded from wells that only penetrate the upper 5 feet of the reservoir. For example, in compartment B4 in the southern portion of the field (fig. 11), none of the wells was drilled through the entire reservoir interval; therefore, additional mobile oil probably can be recovered from this area.

Eliminating or decreasing preferential fluid flow through highly permeable (thief) zones may greatly enhance oil recovery during waterflooding. Well workovers are suggested as a partial solution to the problem of vertical heterogeneities. The wells should be reentered and open hole completions in the Aux Vases should be cased to total depth, then stratigraphically lower permeable zones should be perforated.

Actual well spacing for Aux Vases production in the field considerably exceeds 660 feet. Because the primary target during the development of this field was the Benoist reservoir, many good Aux Vases locations have been ignored. Furthermore, cross section A–A′ (fig. 13) suggests that the scale of geologic heterogeneity in the Aux Vases reservoir is significantly smaller than the current 660-foot well spacing. Correlation of strata is sometimes difficult in wells that are only 660 feet apart. This difficulty in correlating strata is a qualitative indicator of poor reservoir continuity. The relatively low well density and limited number of injector wells in the Aux Vases

Table 1 Values for reservoir fluids at Boyd Field.

Reservoir fluid	Value
Residual oil saturation (%)	
Irreducible minimum	16.1
At approximately 5 pore volumes throughput	24.4
Relative permeability to water (K_{rw} as a %)	
At end point oil saturation	49.6
At approximately 5 pore volumes throughput	27.6
Relative permeability to oil	
Corrected for intersticial water (K_{ro} as a %)	29.9
Oil gravity API @ 60°F	36.8
Oil formation volume factor at saturation pressure @ 331 psi	1.069
Oil viscosity at reservoir temperature	
Centipoise @ 90°F	4.4

make this reservoir an excellent target for additional infill drilling and secondary recovery at Boyd Field.

Superior Oil Company Reservoir Data

In the late 1940s and early 1950s, Superior Oil's research center at Rio Bravo, California, conducted extensive testing of core and reservoir fluids from Boyd Field (Campbell and Rickman Consultants 1954). Table 1 summarizes the production research data from the study. Only this summary is available, therefore, the methodologies cannot be compared with modern methods.

Clay Mineralogy and Potential Problems in Drilling, Completion, and Production

The individual grains in the Aux Vases sandstone are coated with a mixture of three different types of clay minerals: mixed-layered illite/smectite, illite, and iron-rich chlorite (appendix A). Mixed-layered illite/smectite and iron-rich chlorite can cause significant production and completion problems. Iron-bearing chlorite can be a problem if wells are treated with hydrochloric acid for mud clean-out or matrix acidification. Iron is liberated from the clay mineral by the acid and then reprecipitated as ferric hydroxide (McLeod 1984). The precipitate fills pore throats and lowers the permeability of the reservoir. The processes that remove iron from the chlorite can also remove the brucite-like layer from the crystal structure and produce a clay similar to smectite (Simon and Anderson 1990).

Mixed-layered illite/smectite can swell when exposed to freshwater (Almon and Davies 1981), clogging pore throats and greatly reducing permeability. This type of clay mineral has been known to cause problems when drilling with freshwater muds or flooding with water less saline than formation water. Drilling with freshwater mud, the predominant practice in Illinois, can lead to formation damage. As mentioned earlier, shale intervals in the Aux Vases core from the Sanders No. 9 well expanded when sprayed with freshwater (fig. 10b).

The ISGS is currently conducting core flood experiments to investigate the effects of injection waters on the productivity of several Aux Vases sandstone reservoirs, including Boyd Field. These data, methodologies, and interpretations are the subject of a separate report. Results from flow tests on Boyd Field cores suggest that freshwater can cause significant formation damage in the Aux Vases reservoir.

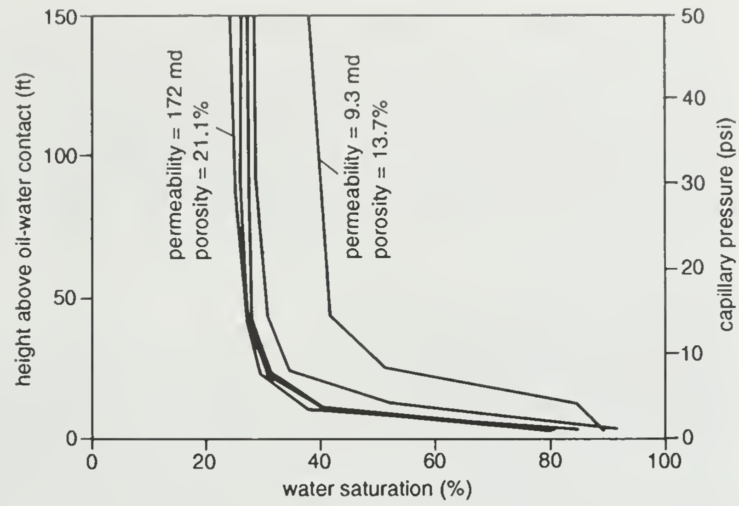


Figure 17 Connate water saturation as the percentage of pore space relative to the height above the free water level. The annotated curves are from the core with the highest and lowest permeability measurements (data supplied by GeoCore Inc. 1992).

When freshwater was injected into the core, permeability values were as much as 50% less than the values obtained when brine was injected. The drop in permeability is irreversible under reservoir conditions; once freshwater has damaged the formation, an injection of fluids with a different salinity will not improve the permeability.

In a waterflood operation where freshwater is the injection fluid, the clay minerals may inhibit flow through the pore throats and therefore increase the pumping pressure. In areas of the field that have not been influenced by the early waterflood, the recommended injection fluid is the brine produced by the Aux Vases reservoir. In the 1940s and early 1950s, Superior Oil Company also conducted core flow tests of the Aux Vases at Boyd Field. The results showed only an 11% drop in permeability when freshwater was injected into the formation. The differences in the results of the ISGS and Superior Oil Company tests could have been caused by one or more of the following: 1) relative abundance and types of minerals in the cores were different, 2) water salinities may have been different, and 3) drying and cleaning processes were probably different. The test results would have been significantly different had the core not been restored to its native state. Recent studies by ISGS and those by Superior Oil some 40 years ago point out, however, that the injection of freshwater decreases permeability.

Fluid to Fluid Incompatibility

During the Boyd Field waterflood, sufficient quantities of brine initially were not produced to run an adequate injection program. The operator, therefore, also injected locally derived, fresh surface water into the two formations. Superior Oil Company found that sufficient quantities of dissolved barium were present in the brine to form a precipitate of barium sulfate when it was mixed with the freshwater. The precipitate tended to plug the injection wells, and significantly increased maintenance costs. It is not clear whether the freshwater was incompatible with the brine because of water chemistries or bacterial effects.

Capillary Pressure Analysis

GeoCore Inc. of Loveland, Colorado, completed capillary pressure analyses of the Aux Vases core taken at a depth of 2,168 to 2,174 feet from the Superior Oil Co. Sanders No. 9 well (appendix B). The capillary pressure curves for the five samples

are shown in figure 17. The results are similar to those of capillary pressure tests run by Superior Oil in the early 1950s (Campbell and Rickman Consultants 1954). The plot of height above the oil–water contact versus connate water saturation shows that the poorer quality reservoir (9.3 md of permeability) has a significantly higher connate water saturation than the better quality reservoirs. Even for the best quality reservoirs, the connate water saturation will be more than 30% at 20 feet above the oil–water contact. Because of the small structural closure at Boyd Field, large portions of the Aux Vases reservoir at Boyd are less than 10 feet above the oil–water contact.

Reserve Calculations

The volumetric method was used to determine the STOOIP (stock tank original oil in place). Reservoir volumetrics were calculated using a single water saturation of 42.7% for the entire field (Campbell and Rickman Consultants 1954). Water saturation values calculated from old electric wireline logs are inaccurate because of the bound water in the abundant micropores of the clay minerals. The average porosity of 20% was based on the average porosity of 26 cores from the reservoir. An estimated 4.6 million barrels of STOOIP was in the Aux Vases reservoir. The measured residual oil saturation in the Aux Vases is 16.1% (table 1) and the original recoverable reserves are 3.3 million barrels.

Unfortunately, the volume of produced Aux Vases oil is unknown. As previously mentioned, commingling of Benoist and Aux Vases production probably reduced Aux Vases production significantly and made accurate estimates of production volume difficult. The 1954 field report of Campbell and Rickman Consultants noted

> ...the presence of salt water continuously in contact with the formation face under varying backpressures as a result of the dumping of water from the higher Bethel formation...probably worked greatly to the detriment of Aux Vases production. Little doubt exists but that the present reservoir pressure of the Bethel formation far exceeds that of the Aux Vases.

The Campbell and Rickman report referred to the Benoist reservoir as part of the Bethel formation.

RESERVOIR CLASSIFICATION

The Aux Vases reservoir at Boyd Field is a structural–stratigraphic trap, consisting of several separate sand lenses affected by an anticlinal structure. The mixture of carbonates and siliciclastics that constitute the Aux Vases reservoirs at Boyd Field was deposited in a tidally influenced, nearshore, shallow marine system. Siltstones, shales, and calcareous facies in the reservoir act as impermeable barriers to lateral and vertical fluid flow and apparently separate the reservoir into four separate lateral compartments and at least three vertically separate flow units.

CONCLUSIONS

Only 48 of the 116 producing wells at Boyd Field were completed in the Aux Vases Formation. Most of the other producing wells were completed in the Benoist sandstone. Many of the 48 Aux Vases wells penetrated only the top 5 feet of the reservoir. The combination of high permeability thief zones and low permeability zones of laterally continuous shales and calcareous layers results in a vertically compartmentalized reservoir. Wells not drilled through the entire producing interval were not able to recover as much of the mobile oil as wells in contact with all of the

vertical compartments. These compartments of bypassed oil are targets for strategic redrilling or recompletion.

Relatively impermeable layers of shale, siltstone, and carbonate separate the Aux Vases reservoir into four distinct lateral compartments that have little or no communication with each other. Although not specifically considered in this report, the current pattern of injector wells and producing wells may not be adequate to efficiently sweep this highly compartmentalized reservoir.

The dual completion of all Aux Vases producing wells in the Benoist reservoir also probably hindered Aux Vases production. The Benoist, a water drive reservoir, has had a higher sustainable pressure than the Aux Vases reservoir, which is predominantly a gas-depletion drive. Water injection into the Aux Vases reservoir should have alleviated the problem; however, packer tests conducted 8 years after water injection began indicate that the higher pressure in the Benoist resevoir was still inhibiting fluid flow in the Aux Vases reservoir.

During water injection, the freshwater that came in contact with the Aux Vases brines generated precipitates that may have contributed to formation damage of the Aux Vases reservoir at the borehole, thus inhibiting production. Preliminary core flow tests of the reaction of the Aux Vases reservoir rock to freshwater injection show freshwater to be detrimental to reservoir permeabilities. Any subsequent drilling and waterflooding must take this into account.

The high degree of lateral and vertical reservoir heterogeneity makes Boyd Field a good candidate for improved oil recovery. A program that involves drilling of new infill wells, both producers and injectors, and completion of existing wells only in the Aux Vases sandstone, should be able to recover additional reserves.

Improved Oil Recovery For Analogous Areas

Key procedures applicable to other mature fields are summarized below.

- Locate reservoirs that are likely to have a high degree of definable lateral and vertical reservoir heterogeneity because these reservoirs may have had the lowest recovery efficiency.
- Identify lateral and vertical distribution of the reservoir and delineate flow units.
- Analyze waterflood patterns and the distribution of injector and producer wells and their completion interval in relation to the compartmentalization of the reservoir.
- Identify similar multi-pay reservoirs that were dually completed and may have pressure differentials.
- Recognize the presence of iron-rich chlorite and mixed-layered clay minerals and perform and evaluate core flow tests.

ACKNOWLEDGMENTS

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APPENDIX A MINERAL COMPONENTS FROM X-RAY DIFFRACTION ANALYSIS

API number	Depth (ft)	Clay index	Mineral analysis (%) Illite	Illite/smectite	Chlorite	Quartz	Potassium feldspar	Plagioclase feldspar	Calcite	Dolomite
01972	2129	0.03	1	1	tr	94	2	1	1	tr
01972	2131	0.03	1	1	2	91	3	2	1	tr
01972	2133	0.02	tr	tr	1	88	1	1	8	tr
01972	2134	0.08	4	3	3	81	1	1	8	tr
01972	2135	0.02	tr	tr	1	67	1	1	28	tr
01950	2141	0.03	1	1	1	81	2	1	13	tr
01950	2144	0.01	tr	tr	1	84	3	1	10	tr
01950	2151	0.04	1	1	2	85	3	2	6	tr
01950	2155	0.02	1	0	1	88	3	1	5	1
01950	2130	0.03	1	1	2	70	3	2	22	tr

API no. 01972, Superior Oil Co. Pasco Price No. 1 well
API no. 01950, Superior Oil Co. Rebecca et al. No. 7 well

$$\text{Clay index} = \frac{4 \times 020 \text{ Clay peak } (19.9^\circ\ 2\theta)}{\text{Adjusted sum nonclay peaks}}$$

APPENDIX B SUMMARY OF AUX VASES CAPILLARY PRESSURE AND SATURATION EXPONENT DATA, SANDERS NO. 9 WELL

Depth	Brine saturation (%)						Resistivity index (R_t/R_o)					
(ft)	1 psi	4 psi	8 psi	14 psi	30 psi	150 psi	1 psi	4 psi	8 psi	14 psi	30 psi	150 psi
2174.0	80.6	40.5	31.6	28.2	28.1	29.9	1.5	7.1	10.1	11.8	11.3	1.7
2168.0	84.7	37.9	29.7	27.5	25.8	23.9	1.5	7.4	14.0	15.7	16.4	19.5
2184.4	89.2	84.5	51.1	41.5	39.9	36.8	1.3	1.5	6.2	7.5	8.7	10.1
2183.0	92.1	52.0	34.5	30.9	28.8	27.8	1.2	4.4	15.8	26.5	20.4	24.2
2171.8	79.8	39.9	30.8	27.4	26.4	29.7	1.6	7.0	13.6	13.6	15.5	12.3

psi = pounds per square inch, R_t = true formation resistivity, R_o = resistivity of formation completely filled with water

APPENDIX C RESERVOIR SUMMARY

Field Boyd Field

Location Jefferson County, Illinois; Sections 18, 19, 30, T1S, R2E; Sections 13, 24, 25, T1S, R1E

Tectonic/Regional Paleosetting Illinois Basin

Geologic Structure anticline

Trap Type structural–stratigraphic

Reservoir Drive gas depletion

Original Reservoir Pressure NA

Reservoir Rocks
Age Upper Valmeyeran of the Mississippian Period
Stratigraphic unit Aux Vases Formation
Lithology sandstone
Wetting characteristics (oil/water) NA
Depositional environment mixed siliciclastic-carbonate nearshore
Productive facies nearshore siliciclastic
Petrophysics (ϕ, k from unstressed conventional core; S_w from logs)

	Average	Range	Cutoff
ϕ	18%	7%–30%	11%
k air(md)	240	38–833	50
k liquid(md)	NA	NA	NA
S_w	45%	NA	NA
S_{or}	NA	NA	NA
S_{gr}	NA	NA	NA
Cementation factor	1.7	NA	NA

Source Rocks
Lithology and stratigraphic unit New Albany Group (Devonian–Mississippian); shale
Time of hydrocarbon maturation NA
Time of trap formation NA

Reservoir Dimensions
Depth absolute (subsea) 2,140 (1,600) feet
Areal dimensions 1,200 acres
Productive area 1,200 acres
Number of pay zones 3
Hydrocarbon column NA
Initial present fluid contacts varies between 1,615 and 1,623 feet
Average net sand thickness 15 feet
Average gross sand thickness NA
Net/gross NA
Initial reservoir temperature NA
Fractured natural, NA; artificial (type), nitroglycerin

Wells
Spacing 10 acre
Pattern NA
Total 130 (116 producers, 0 water source, 0 observation, 15 injections, 0 disposal, 9 dry holes)

Reservoir Fluid Properties

Hydrocarbons

Type oil
GOR NA
API gravity 36.8°
FVF 1.069
Viscosity 4.4 cp
Bubble-point pressure NA

Formation water

Resistivity NA
Total dissolved solids (ppm) NA

Volumetrics

In-place 4.6 million barrels of oil (STOOIP)
Cumulative production NA
Ultimate recovery
Primary NA
Secondary NA
Additional recovery from infill drilling and secondary NA
Secondary (incremental) NA
Tertiary (incremental) NA
Recovery efficiency (factor)
Primary NA
Secondary NA
Tertiary NA

Typical Drilling/Completion/Production Practices

Completions open hole, NA; cased, NA
Drilling fluid Bentonite in freshwater
Fracture treatment 5000 gallons of oil and 7500 pounds of sand
Acidization NA
Other NA
Producing mechanism
Primary (indicate any period of flow) gas depletion
Secondary waterflood
Tertiary NA

Typical Well Production (to date)

Average daily NA
Cumulative NA
Water–oil ratio (initial/cumulative) NA